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Binaries as astrophysical laboratories: an overview

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Abstract.
The study of binary stars is worth to undertake not only to learn more about the properties of binaries as such, but also because binaries are multi-purpose astrophysical tools. This paper reviews some of the ways this effective "tool" can be used, focusing on fundamental parameter determination, tests of theoretical models, and the recent contribution of binary stars to establish the distance to the Magellanic Clouds, and therefore, the first rungs of the cosmological distance ladder.

1. Introduction: binarity as a benefit

A recurrent activity of the astrophysicist involved in binary star research is "advertising" binaries as effective astrophysical tools. It could seem hardly necessary, as the the role of binaries in laying the foundations of stellar astrophysics is, in principle, very well known. Too often, however, the complexity that a binary configuration can add to observations, to data analysis and interpretation, overtake the large amount of information that could, nevertheless, be extracted from binarity.

To fully exploit the binary assets accurate, and sometimes lengthy, observations are needed. In some cases (as for spectroscopy of extragalactic binaries) world-class instrumentation is required, that is rather difficult to obtain for the necessary number of nights. Therefore, it is important to stress that the efforts to better understand binary stars yield as well "by-product" useful results for stellar astrophysics.

Binaries are the primary source of fundamental stellar parameters and an important benchmark of theoretical models. Double-lined eclipsing systems offer a *purely geometrical* means of determining stellar radii and masses. Besides, well before the amazing achievements of asteroseismology, binaries provided a probe to stellar interiors through the study of apsidal motions and of secular orbital evolution and synchronization. Basic information about the stellar structure (mean densities, size of convective cores) can indeed be derived from the long term study of their best known parameter, the orbital period, or from studies of period distribution and synchronization of suitable samples.

In recent years, double lined eclipsing binaries have proven as well to be accurate distance indicators to clusters in our galaxy or even to the galaxies of the local group, providing independent determinations and tests of the first rungs of the distance ladder. Moreover, the quick development of interferometric techniques is opening the possibility of directly deriving effective temperatures and

Table 1. Parameter determination at glance

Element	AB		SB		EB
	VB	IB	SB1	SB2	
a	a''	a''	$a_1 \sin i$	$a \sin i$	N
e	Y	Y	Y	Y	Y
P, T_0	Y	Y	Y	Y	Y
i	Y	Y	N	N	Y
ω	Y	Y	Y	Y	Y
Ω	$\pm 180°$	$\pm 180°$	N	N	N
m_1, m_2	with absolute orbit and π		$f(m)$	$m_i \sin^3 i$	N
R_1, R_2	N	R_i''	inferred from Sp. and L		$r_i = R_i/a$
L_2/L_1	Y	Y	N	from Sp.	Y
limb dark.	N	y	N	N	y
gravity dark.	N	y	N	N	y

atmospheric properties of an increasing number of binary components, a very important result, that will allow to "close the loop" of fundamental parameter determination.

Finally it has to be stressed that, anyway, binaries cannot be ignored, for the simple reason that *multiplicity is the rule*, not the exception. Fifty to seventy percent of all stars, at least in the solar neighborhood, are members of binary or multiple systems. Therefore, the formation and evolution of stars (and of clusters and galaxies they populate) cannot be really understood without a deep knowledge of binary stars.

2. Binaries to determine the fundamental stellar parameters

We will distinguish between the determination of stellar masses and radii, relying on pure geometrical methods, and the less direct one of effective temperatures.

2.1. Stellar masses and radii

Conceptually, the simplest derivation of stellar masses stems from astrometric binaries with known *absolute* orbits of the components (with respect to nearby stars) and known parallax. This is, indeed, the only case in which the mass determination can be achieved by only one technique (see Table 1). The table – an updated version of the similar one from the classical book of Batten (1973) – gives a summary of the parameters that can be derived (or inferred) from astrometric binaries, (AB) subdivided into visual (VB) and interferometric (IB) binaries, double and single-lined spectroscopic binaries (SB2, SB1) and eclipsing systems (EB). The first seven parameters in the table define the orbit: semiaxis, a, eccentricity, e, orbital period, P, epoch of primary minimum, T_0, inclination, i, longitude of periastron, ω, and orientation of the line of nodes, Ω. The remaining

parameters are the component masses, radii, ratio of luminosities (usually in a color band), and the parameters defining second order effects in the light curve (limb and gravity darkening). The small 'y' means 'yes, in particular cases' (such as, for instance, with high accuracy observations). The value of Ω is ambiguous by 180° if determined by visual observations alone.

IBs, similarly to VBs, provide a way to reconstruct the orbit and have as well a number of other advantages: a larger limiting distance, the possibility of determining as well the (angular) stellar radii and, in favorable cases, even the limb and gravity darkening (see, for instance, the comprehensive review of Quirrenbach 2001). Most of the main parameters can be determined from ABs

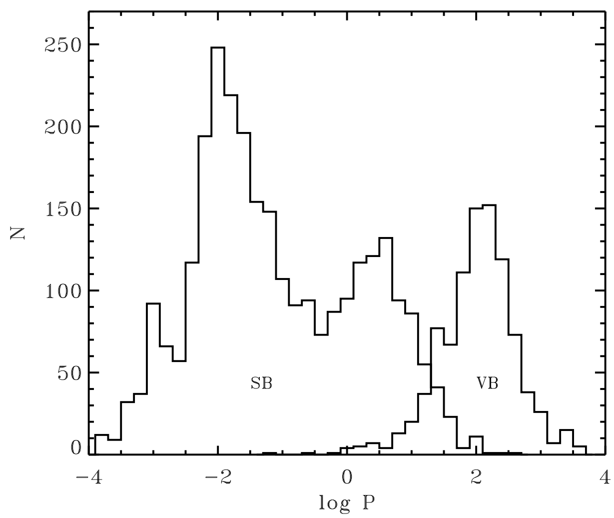

Figure 1. Period distribution from the SB^9 catalog of spectroscopic binaries (Pourbaix et al. 2005) and the 4^{th} Catalog of Visual Binary Orbit (Worley & Heintz 1983)

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of known absolute orbits, if the the linear scale is introduced by the parallax, π. The system total mass directly descends, then, from the 3$^{\rm rd}$ Kepler law, and the mass ratio from that of the orbital semi-axes. Absolute orbits, however, are available for very few systems.

Alternatively, a second relation involving masses can be obtained from spectroscopy and, if the radial velocity amplitudes of both components are known (SB2), the linear scale is provided by the direct determination of $a \sin i$, so that parallax is no longer needed. This applies to a larger number of systems and to larger distance (limited by astrometry), but the intersection of the two samples, VB $\cap$ SB, is still marginal, see Fig.1. That is easily explained by the fact that "typical" visual binaries (as those collected in catalogs) were observed either by eye or by filar micrometers, and the minimum measurable separation was around $0.2''$. The radial velocity amplitude of a nearby system with that separation, total mass of 2 $M_\odot$, and at a distance of – say – 10 pc is in the range $5 \div 15$ Km s^{-1}, depending on the mass ratio (and with circular orbit, i=90°and $q = 0.2 \div 1.0$). The quantity scales, for a given angular separation, as $d^{-1/2}$.

Therefore, even if pointed observations of specific targets with modern instrumentation (such as optical interferometers and high resolution spectrographs on large telescopes) can provide minimum angular separation of a few milli-arcseconds (see below) and radial velocities < 1 Km s^{-1}, there is no surprise for the small intersection of the two distributions of Fig.1.

Furthermore, the accuracy of the masses obtained by this means is typically not very high, the main reason being the dependency of the mass on $\sin^3 i$, so that face-on (low inclination) system do not allow precise determinations. According to a study by Pourbaix (2000) on eighty ABs, only 10% of systems has masses known to better than 3%.

The situation is, however, quickly evolving with the development of new generation interferometers. To cite just one, striking, result: recently Boden et al. (2005) have determined the masses of 12 Boo components with $\simeq 0.4$ % accuracy using the Palomar Testbed Interferometer (PTI) and echelle spectroscopy. This system has a period $P = 9.6^{\mathrm{d}}$and an apparent separation of only 3.45 mas (and $\pi = 27.74$ mas).

The latest development of long baseline interferometry, with new generation instruments already in operation (such as the CHARA array) or planned for next future, is pushing the resolution limit to values well below the mas. The basic formula expressing the resolution of an interferometer, $R = \lambda/2b$, where b is the baseline and λ the wavelength, tells us that to resolve, for instance, a spectroscopic binary with a separation of 40 $\mathrm{R}_\odot$ and at a distance of 500 pc (i.e with an angular separation of 0.4 mas) a baseline of $\simeq 300$ m is needed, a value that is comparable, for instance, to the longest one of CHARA array. Space-born experiment (such as SIM, Stellar Imager) will, of course, go much beyond.

By now, however, the "royal road" to stellar mass determination is still traced by double-lined eclipsing binaries (eSB2). The detailed analysis of detached eSB2s yields masses with an accuracy often better than 1%, i.e. suitable as stringent tests for theory (according to Andersen (1991) a 1%-2% accuracy in stellar parameters is necessary to really constrain the models). The main limitation, in this case, is the rapid decrease of the eclipse probability with orbital period. For given masses and radii this quantity scales approximately as $P^{-4/3}$ (Maceroni & Rucinski 1999).

According to the results of photometric surveys, as OGLE, MACHO, Vulcan, STARE, ASAS, 0.1–0.2 % of stars are eclipsing binaries: our galaxy should contain, therefore, $\sim 10^8$ EBs. Only two hundred systems, however, have been studied in detail (out of ~ 10000 presently known), and for only half of those accurate parameters could be determined (Andersen 1991, 1998, 2002). Some stellar types are dramatically under-represented among EBs (low and high mass stars, giants), though the situation is steadily improving, thanks to the results of the abovementioned surveys.

Eclipsing spectroscopic binaries provide as well precise (at a few percent level) stellar radii. The great advantage is that the radii (as the masses) determined by eSBs are distance independent. An alternative source is, also in this case, long baseline optical interferometry. This requires, anyway, the transformation to the linear scale of the measured angular diameters. More than hundred stellar radii determinations can be found in the literature: obtained by

the Narrabri Intensity Interferometer and VLTI (Hanbury Brown et al. 1974; Di Folco et al. 2004) for hot stars, by the Mark III, NPOI (Naval Prototype Optical Interferometer) and PTI (Mozurkewich et al. 2003; Nordgren et al. 1999; Lane et al. 2001) for cooler stars. If the object under study is a spectroscopic binary (or has a known parallax) the linear diameters can be obtained. The accuracy of angular diameters by interferometric measurements can vary from 0.5% to a few or several percent, depending on the system characteristics and the wavelength (redder wavelengths provide more accurate results). In general the binary case is more difficult to treat than that of single stars.

To be noticed that interferometric and eclipsing binaries results are somewhat complementary, the sample of stars studied by interferometry contains, in fact, many giants which are scarce among EBs.

2.2. Stellar temperature, luminosity and distance

For comparison with stellar models or distance estimate the effective temperatures are needed. These can be obtained by different methods:

- empirical calibrations and absorption free color indexes (e.g. from Strömgren or IR photometry). The distance is derived from the distance modulus by the standard expression:

$$(m_{\rm V} - M_{\rm V})_0 = m_{\rm V} - A_{\rm V} - M_{bol,\odot} + 5\log\frac{R}{R_\odot} + 10\log\frac{T_{\rm e}}{T_{{\rm e},\odot}} + {\rm BC}. \quad (1)$$

  The typical uncertainties of the various quantity appearing in Eq. 1 were estimated by Clausen (2004), in the application to distance estimation of the LMC, and imply a distance modulus accuracy of 0.10-0.15 magnitudes, with somewhat better results for early type stars ($0.07 - 0.09$ mag). These are characterized by a favorable behavior of the bolometric correction with temperature: a linear fit of the early star region of the Flower (1996) ($\log T_{\rm e}$–BC) calibration yields BC$\propto -5.4\log T_{\rm e}$, so that the dependence of their distance modulus on $T_{\rm e}$ is weaker than appearing from Eq.1.

- for SB2-EBs: fit of the UV – optical SED, avoiding the use (and uncertainties) of calibrations (Guinan et al. 1998; Fitzpatrick & Massa 1999). The measured flux, $f_{\lambda,\oplus}$, can be expressed as function of the stellar radii, the surface fluxes, $F_{\lambda,i}$, the distance, the absorption coefficient and color excess:

$$f_{\lambda,\oplus} = \left(\frac{R_1}{d}\right)^2 \left[F_{\lambda,1} + \left(\frac{R_2}{R_1}\right)^2 F_{\lambda,2}\right] \cdot 10^{-0.4[E(\lambda-V)+A_{\rm V}]} \quad (2)$$

  The surface fluxes, $F_{\lambda,i} = f(T_e, \log g, m/H, \mu)$ can be derived from model atmospheres (the surface gravities are known, the microturbulence velocity, μ, is held fixed). A best fit for T_e, m/H (metallicity), $A_{\rm V}$, $E(\lambda - V)$, d provides the temperatures, the characteristics of interstellar absorption and the distance. The method has been applied with success to several extragalactic eSB2s. The procedure is rather complex, requires multi-wavelength data and is better applied to hot stars in a temperature range

free from NLTE effects, which can be a problem for model atmospheres (i.e below 30000 K). The results can be, however, of great accuracy. For instance, the effective temperature of the HV 2274 primary component, as obtained by Guinan et al. (1998), is $T_e = 23000 \pm 180$ K.

- The method of infrared fluxes (Blackwell & Shallis 1977; Blackwell & Lynas-Gray 1994) is based on the weak dependence of the IR flux on T_e and benefits of the negligible interstellar absorption at IR wavelengths. In the single star case, an iterative process starting from a guessed T_e and model atmospheres (to compute the surface flux F_{IR}) provides, because of the abovementioned weak dependence, a precise value of the ratio:

$$\frac{f_{IR,\oplus}}{F_{IR}} = \frac{\theta}{4}^2 \tag{3}$$

That yields, in its turn, the value of the angular diameter, θ. An improved value of T_e can then be obtained from the measured integrated flux at Earth, by means of the relation:

$$f_{\mathrm{bol},\oplus} = \frac{\theta^2}{4}\sigma T_\mathrm{e}^4 \tag{4}$$

from which a new iteration can be started. A straightforward extension of this method to binary stars has been formulated by Smalley (1993).

The method yields late type star temperatures determined with 1.3% accuracy (Ramírez & Meléndez 2005) and, as well, angular radii that agree within 1% with interferometric determinations (Nordgren et al. 2001). It is obvious from Eq. 4 that, in the case of nearby stars, the effective temperatures can be directly derived from the interferometric angular diameters and bolometric fluxes.

- The detailed spectral analysis after applying, if necessary, an algorithm for component spectra disentangling (Hadrava 1995).

3. Using the binary tool

For reasons of space it is impossible to examine in detail all the ways binaries can be used as effective "astrophysical tools". I will focus, therefore, on their effectiveness as benchmark for stellar models and on their recently acquired role of independent contributors to the first rungs of the distance scale. Other important topics, such as the study of apsidal motion, of spin–orbit synchronization and circularization, yielding precious information on stellar structure, have been reviewed by several authors in a recent conference (Claret et al. 2005).

3.1. Binaries as theoretical model benchmarks

Fig 2 shows the mass – luminosity relation of Henry (2004) derived from binaries with accurate elements. The upper part of the plot is populated by EBs, the lower one essentially by ABs (with larger errors). Only a handful of low mass eSB2s are known. At the other end, the most massive stars have

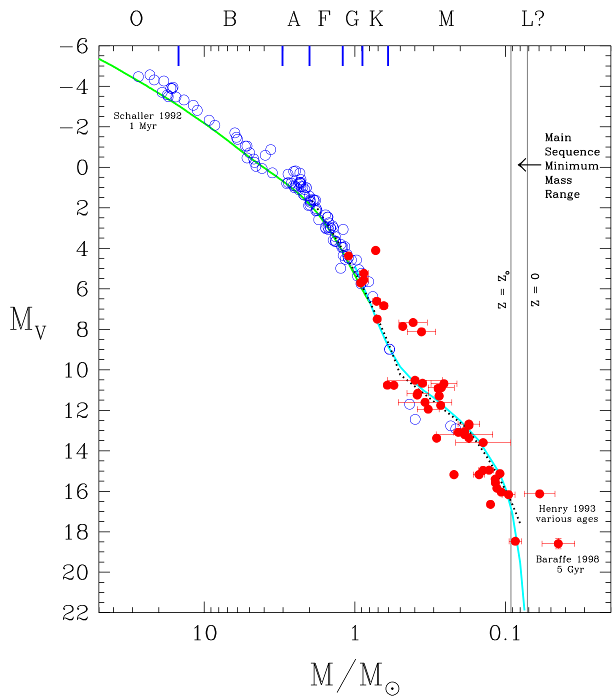

Figure 2. The Mass-Luminosity relation for field stars according to Henry (2004). Open points represent eclipsing binaries, solid points astrometric binaries. The fit in the massive star region is from Schaller et al. (1992), in the low mass one from Baraffe et al. (1998). An empirical fit (dotted line) from Henry & McCarthy (1993) and Henry (1999) is also shown.

$M \cong 30$ $M_\odot$. It has to be mentioned that the mass record actually belongs to the recently analysed double-lined eclipsing binary WR20a, member of the open cluster Westerlund 2. The system is formed by Wolf-Rayet components of 83 ± 5 and 82 ± 5 $M_\odot$ (Bonanos et al. 2004), the largest directly determined masses. AS the figure collects only MS binaries, neither WR20a nor the few known eSB2 with (sub)giant components are included.

Fig. 2 shows a fair agreement between theoretical models and observations, but the data cannot be used to really constrain the models, because of the intrinsic scatter due to age and metallicity effects. Besides, the most stringent constraints are those posed by masses and radii, or surface gravities. When accurate values of these quantities are compared with standard theoretical models several discrepancies appear.

For instance, Andersen (1998) showed that the surface gravities (derived with precision better than 2 %) of a sample of intermediate mass MS eSB2 components are smaller than the values expected from standard models (see Fig.1 of the abovementioned paper). That is explained in terms of the inadequacy of the treatment of internal mixing: to fit the observations a convective core larger than that of standard models is needed, implying a certain amount of extra mixing. By the way, models with larger convective core are more centrally condensed, in agreement, as well, with the results from the studies of apsidal mo-

tions. This requirement has been modeled, in absence of a physically consistent description, by introducing core overshooting in a parametric form. The obvious disadvantage of the parametric treatment is that the physical model cannot be tested, though in some cases very high values of the overshooting parameter are obtained which are difficult to accept.

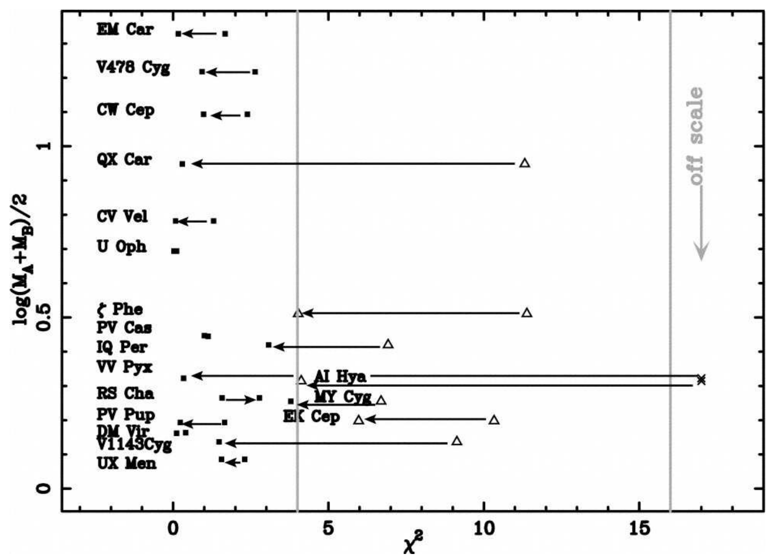

Figure 3. The χ^2 values for best models of binaries vs the mean system mass from Young & Arnett (2005, courtesy of ApJ). Arrows are drawn from the χ^2 values obtained by Young et al. (2001) with standard models by the same code, to the values from the updated 2005 version, including extra-mixing by internal waves. The vertical line at $\chi^2 = 4$ indicates a fit in which the models fall inside – in the $\log R - \log L$ plane – the observational error boxes of both components.

A different approach has recently been proposed by Young & Arnett (2005), who find a very good agreement between the observed parameters (radii and luminosities) of a subset of the Andersen (1991) sample, made out of 18 eSB2s with MS components and masses in the range $1.2 \leq M \leq 30$ $M_\odot$, and the models from their evolutionary code TYCHO. The last version of TYCHO includes a consistent treatment of mixing by internal waves, which has on the stellar structure an effect similar to overshooting, but introduces no free parameter. The fit, performed by a χ^2 algorithm (in the hypothesis of equal age for both components) greatly improves when extra mixing is taken into account, all stars fall within the error boxes in the $\log R - \log L$ diagram, see Fig.3.

A second, still open, issue concerns the results of testing low mass models. Only in the last years a (still small) number of eSB2s has been added to the two well known calibrators of the lower MS, YY Eri and CM Dra, often thanks to the completeness of variability searches of photometric surveys. These are: CU Cnc (Ribas 2003), GU Boo (López-Morales & Ribas 2005), OGLE BW3V38 (Maceroni & Montalbán 2004) and TrES-Her0-07621 (Creevey et al. 2005). The study of these systems has revealed the existence of a systematic discrepancy between models and observations, in the sense that real late K–M dwarfs seem

to have larger radii (up to 20 %) and lower effective temperatures (by as much as 150 K) than current models (see Ribas contribution, these proceedings). Among the suggested explanations the most likely is the presence of strong magnetic fields. The non-standard stellar models of Mullan & MacDonald (2001), which include a simplified treatment of magnetic field effects, suggest that late-type active stars (hosting magnetic fields up to several tens of MGauss at the base of the convective zone) should have, indeed, larger radii and lower temperatures than similar, inactive, dwarfs. In this case as well binaries point out the need of non-standard ingredients in stellar models.

3.2. Photometric surveys and rare binaries

The photometric surveys for variability search as OGLE, MACHO and their related programs [1] yielded, indeed, many by-product discoveries of interesting and rare binary systems, including a few eclipsing binaries with pulsating components (that could provide an independent determination of the pulsating component mass with spectroscopy follow-up). Three candidate eclipsing binaries containing an RR Lyr component were discovered by OGLE-III in the LMC (Soszynski et al. 2003), while three EBs with Cepheid components in the MACHO database of LMC variable stars have been studied in detail by Alcock et al. (2002).

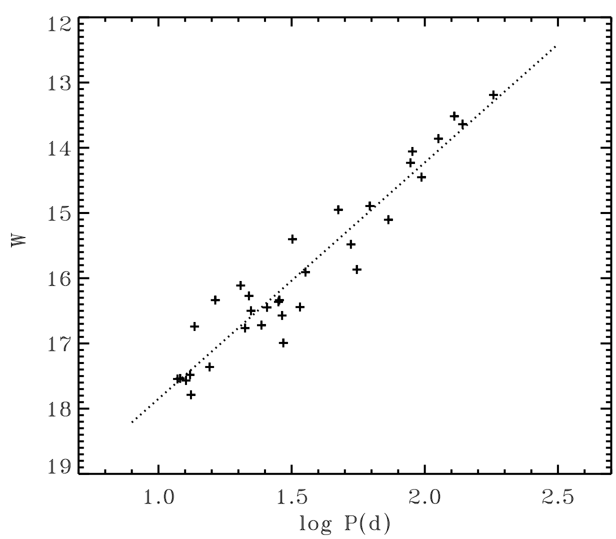

Figure 4. The relation between the Wesenheit index, W, and orbital period for the 35 binaries with ellipsoidal giant primary extracted by Rucinski & Maceroni (2001) from the OGLE-II SMC catalog of variable stars.

Besides, a new class of interesting binaries, with periods in the range $10 \div 180^{\mathrm{d}}$, and whose light curves are produced just by the ellipsoidal variation of a giant primary, was identified by Rucinski & Maceroni (2001) in the SMC fields

[1] a quite complete documentation is available at http://wwwmacho.mcmaster.ca/ and http://sirius.astrouw.edu.pl/∼ogle/

observed by the OGLE-II experiment. These objects, thanks to the scaling with period of an essentially fixed geometrical configuration (primary in contact with the Roche lobe), follow a period/color/luminosity relation and can be used as auxiliary (but independent) distance indicators. Fig.4 expresses this property trough the relation between the orbital period and the Wesenheit absorption-free color index, $\mathrm{W = I - 1.55(V - I)}$, generally used for pulsating stars. In terms of absolute V magnitude and color index the P-L-C relation can be written as:

$$M_V = -3.43 \log P + 2.04\,(V - I)_0 + 2.80, \quad \sigma = 0.34 \tag{5}$$

where σ is the standard deviation of the fit of the 33 systems with ellipsoidal giants of Rucinski & Maceroni (2001). The same type of eclipsing binaries were, later on, detected in large number in the LMC (Soszynski et al. 2004). The brightest of the LMC samples obey a relation similar to that in Fig. 4, differing for a shift by an amount close to the difference in distance modulus between the Clouds.

3.3. Binaries and the distance ladder

As shown in the previous sections, the detailed analysis of detached eSB2s is in itself a powerful tool to measure distance. The idea of using binaries as distance indicators to clusters and to the closest members of the Local Group dates back, indeed, to the first half of the 20th century (Gaposhkin 1940), i.e. about thirty years after the discovery by Leavitt (1908) of eclipsing binaries in the Magellanic Clouds. It was necessary, however, to wait some decades more to achieve the necessary technical and instrumental development. The first modern and accurate determination of the LMC distance modulus by a detached eSB2, the Harvard Variable HV2274, is due to Guinan et al. (1998), previous attempts having essentially an historical interest.

Since then, a few other systems have been studied, providing clues of a non-negligible depth of the Cloud along the line of sight (Guinan 2004). A parallel analysis of binaries in the Small Magellanic Cloud has been undertaken by Harries et al. (2003).

In both cases the binary-based results are in excellent agreement with the determinations by other means and have an accuracy comparable to that of the best indicators. The latest estimate for the LMC, according to Guinan (2005) is $(m-M)_0 = 18.42 \pm 0.07$, in good agreement with the value to which the various other results seem to converge (the weighted average from different methods, according to Alves (2004) is 18.50 ± 0.02).

Similarly, the SMC distance modulus, as obtained by Harries et al. (2003); Hilditch et al. (2005) from fifty EBs, is $(m - M)_0 = 18.91 \pm 0.03 \pm 0.1$ (the last term being an evaluation of systematic errors). The value is in between the " long" distance derived from Cepheids (see, e.g., Bono et al. 2001) and the "short" one from red clump stars (e.g Twarog et al. 1999).

With the availability of 10m-class telescopes, it is now feasible to get the first spectroscopic observations of eSB2s in galaxies of the Local Group. Several hundreds EBs have been detected by photometric surveys in M31, a few tens in M33 (Bonanos et al. 2003; Macri 2004). A few EBs have been found as well in the smaller members of the local group: Fornax, Leo, Carina, NGC 6822 (see Guinan 2004, and references therein), and Phoenix (Gallart et al. 2004). The

first, preliminary, determination of the distance to M33 by means of an eSB2 has been recently obtained (Bonanos et al. 2005). No doubt therefore that this field, in very rapid development, will yield fundamental contributions to the knowledge of nearby galaxies and of the Universe.

4. Conclusions

The fact that in our galaxy the majority of stars are components of binary or multiple systems is for us a great stroke of luck, as we got efficient and versatile tools to increase our knowledge of stars in the Milky Way and other galaxies.

The technical developments of the last decades has opened the possibility of studying binaries in the Magellanic Clouds, in M31 and in M33, and of accurate determinations of their absolute elements and distance. On one side, this allows to study different stellar populations from those of our galaxy, on the other it provides an independent and scale free distance indicator. The results from binaries for the distance to the LMC, which is responsible of a non negligible contribution to the error budget in the determination of the Hubble constant, are of great value, being free from zero-point uncertainties. While at present accurate distance determinations are possible only for the Magellanic Clouds, because of the magnitude limits for spectroscopy, in the next future the other members of the Local Group, in which many eclipsing binaries have already been detected, will become reachable. The first example in this direction is the first determination of the distance to M33 obtained by spectroscopy with the Keck telescope.

The large databases and catalogs from microlensing and planet-search surveys of the last decade have already provided light curves of about 15000 eclipsing binaries. Many interesting and rare system were found and a complete analysis was possible after follow-up observations. The next future reserves an increase of two more order of magnitudes, millions of light curves will be provided by wide-field all-sky surveys, and at different wavelengths. It will be imperative, therefore, to develop ad-hoc automatic algorithms for data reduction and analysis.

Space experiments devoted to asteroseismology and planet searches (such as Corot and Kepler) will provide, as well, extremely precise and continuous photometry (at a level of 10^{-4} mag and on baseline of months or years) of many thousand binaries. Detailed study of the stellar atmospheres (from, e.g. the direct determination of the limb darkening from the light curves) will be possible, together with a long term monitoring of stellar activity phenomena. Certainly many new objects belonging to the present groups of rare binary systems will be found.

Finally, interferometry is already filling the gap between spectroscopic and visual binaries, providing more and more accurate stellar parameters for closer and closer systems. In the next future close binary systems will be routinely resolved by long baseline optical interferometers and space missions, as Stellar Imager, will be able to resolve surface features on the individual components.

Therefore, the classical field of research on binary stars has still an extremely bright future, promising great developments and interesting research topics for you all.

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